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Optimization of the tether-assisted return mission of a guided re-entry capsule

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Abstract

This paper presents the mission analysis of a tether-assisted payload retrieval from the International Space Station (ISS). The objective is to assess all relevant phases of such a mission in order to allow a comparison with a conventional mission employing a propulsive deorbitation. The controlled tether deployment procedure and the guided return flight of the released re-entry capsule are optimized. A preferable deployment strategy is identified that allows for favorable entry conditions and low flight loads. The optimal deployment trajectories serve as a basis for an optimal dynamic regulator. This approach is extended towards an adaptive concept, where artificial neural networks are applied to deployment control. For the guidance of the capsule a predictive concept is proposed that is based on the optimal re-entry trajectories identified previously. By applying these concepts, the attainable landing accuracy during return amounts to an average of 5 km, and the application of the tether system exhibits overall system mass advantages. This demonstrates that the tether-assisted return mission is a competitive alternative.

Keywords: Optimal tether deployment; Re-entry guidance; Sample return capsule; Adaptive control; Neural networks

1. Introduction and motivation

Future utilization of the experimental facilities on board the ISS exhibits a demand for frequent return opportunities. Transport of small payloads, e.g. materials processed in space, and quick access to the samples by the users can be provided by means of small unmanned re-entry vehicles, preferably controllable semi-ballistic capsules. A promising approach is the concept of a tether-assisted deorbitation of such re-entry capsules without resorting to conventional fuel consuming propulsion, Fig. 1. The deorbit maneuver requires an accurate execution of the tether deployment and release of the capsule in order to provide a sufficient landing accuracy that in turn limits recovery efforts. This alternative deorbit concept recently gained much interest and several experimental missions have been proposed, e.g. [7] and [14].

In the present paper all relevant mission phases are optimized and innovative control concepts are applied. The selection of a suitable tether deployment strategy is based on numerical optimization that was so far only applied by a few authors such as in [6], however there constrained to a vertical deployment. The present study extends those investigations towards a dynamic release of the capsule. Furthermore, key parameters affecting the return flight such as the perigee reduction and tether length are considered in the optimization. While optimal deployment trajectories are typically based on a simplified modeling approach [6], the present assessment is extended towards the application of a continuous tether model [18] to demonstrate the validity of the chosen deployment strategy. Applying these optimal profiles directly to the development of an adaptive controller using neural networks extends previous investigations [12] in this area. Earlier studies either assume a ballistic vehicle [16] or the achievable performance of a guided re-entry is not assessed. The present study addresses this mission aspect as an integral part of the analysis.

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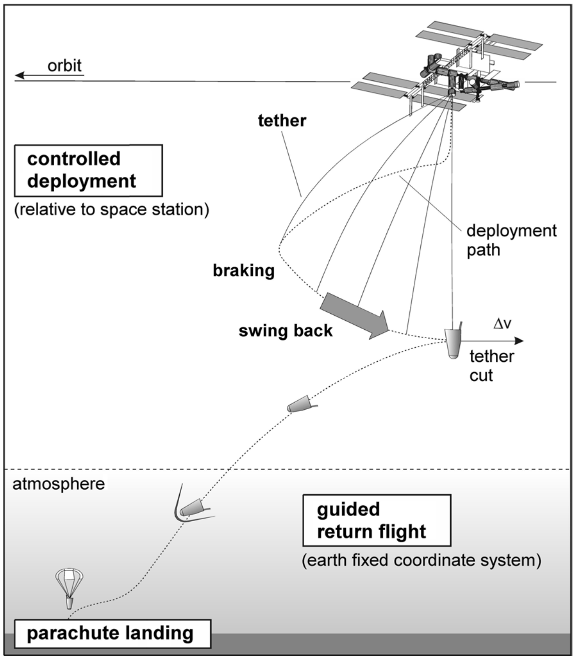

Fig. 1. Tether-assisted return mission from the ISS.

2. Tether-assisted deorbit maneuver

Two possible options to perform a tether-assisted deorbit maneuver are the static and the dynamic release. In both cases, deployment from ISS is initiated by giving the capsule an initial separation velocity of typically 0.5–1 m/s in a downward direction. Active braking by a deployment mechanism becomes necessary to guide the capsule along a predefined deployment path. The two options are characterized as follows:

Static Release: The capsule is deployed near the local vertical towards a specified altitude below the station, where at an appropriate time the capsule is disconnected from the tether and due to momentum exchange enters into a re-entry trajectory.

Dynamic Release: The capsule is deployed towards the maximum tether length and a particular large angle. While the deployment speed is reduced and finally arrives at zero, a swing back motion occurs in the opposite of the flight direction. By cutting the tether close to the local vertical the inertial velocity of the capsule is further reduced compared to a static release.

The achievable perigee reduction of the future elliptic transfer orbit of the re-entry vehicle after tether release with respect to the space station orbit is a function of the tether length l and the maximum in-plane angle reached during deployment. The perigee radius has to be defined such, that the transfer orbit intersects the atmosphere. Typical values correspond with the radius of the earth. In [21] it is shown by analytical approximation that a given perigee reduction may be achieved by a dynamic release for a significantly reduced tether length as compared to a static maneuver. Therefore, only a dynamic maneuver is considered in the present study. For this type of application typical tether masses are in the range of 0.3–0.7 kg/km [21].

3. Numerical modeling

3.1. Modeling of the tether system

Various methods for the dynamic modeling of a tether exist. Among these are formulations that describe the tether as a continuum [18], connected point masses [15], or even as massless [2]. The latter approach yields the advantage of low computational effort that is required for optimization purposes. The acting forces along the tethered system are the centrifugal force and the gravitational force. The resulting force, called gravity gradient force, yields a restoring normal component and a radial component that stretches the tether. Three closely related centers may be distinguished: the center of orbit, the center of gravity, and the center of mass. For short tethers (< 100 km) the difference in position is negligible [21].

The system may be idealized as two point masses connected by a massless, inextensible tether. For a station mass (≈ 415 t) that exceeds by far the mass of the capsule (170 kg), the center of orbit can further be assumed to be situated at the deployer (ISS), thus moving in a circular orbit of 400 km altitude. The corresponding coordinate system is depicted in Fig. 2, where θ denotes the in-plane angle and φ the out-of-plane angle. To derive the equations of motion as defined in [20], the Lagrangian of the system according to [2] is used. The equations describe the relative motion of the capsule with respect to the station. The state and control vectors are given by

$$\vec{x} = [\theta, \varphi, l, \dot{\theta}, \dot{\varphi}, \dot{l}]^{\mathrm{T}} \quad \text{and} \quad \vec{u} = [F_B], \tag{1}$$

where the braking force $F_B \geqslant 0$ corresponds to the tether tension in case of a massless tether.

3.2. Modeling of re-entry flight dynamics

The baseline vehicle for this investigation is taken from the COLIBRI study [3] and represents a sphere-cone configuration with a flattened bottom surface. The capsule is 1.52 m long, equipped with a body flap for aerodynamic trimming and a cold

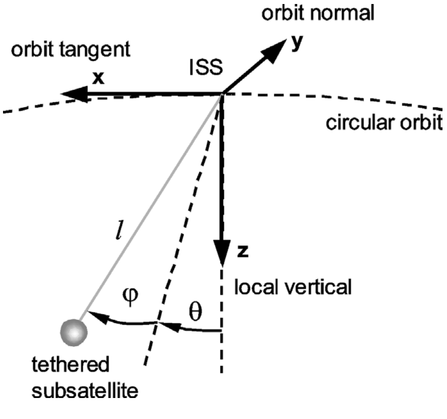

Fig. 2. Coordinate system.